

EJECTA HAZARD RANGES FROM UNDERGROUND MUNITIONS STORAGE MAGAZINES

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INTRODUCTION

Current ejecta quantity-distance (Q-D) criteria for underground munitions storage magazines are based on a few large, high explosive tests, coupled with a limited number of model and full-scale experiments in igloos and underground magazines. The ejecta hazards from accidental detonations in underground magazines are from two sources: overburden rupture and venting (shallow storage chambers), and the breakup of the access tunnel portal or material (including unexploded ordnance) expelled through it. Over the past decade, launch velocity curves for overburden ejecta have been developed in Norway, as a function of cover depth and chamber loading density. This paper describes the analyses conducted and the relation found between the Norwegian launch velocity curves, a simple computational model, and existing ejecta data.

COVER RUPTURE

The primary variables which govern rupture (or cratering) of the overburden above an underground munitions storage chamber are the chamber loading density, cover thickness, and to a limited extent, overburden material. Because of the air volume in the underground chamber, these explosions are not fully coupled to the soil or rock in which the magazine is constructed, and therefore are less efficient in rupturing (cratering) the overburden and producing ejecta than the standard buried charges which are the source of most cratering data. The difference is mainly one of degree, however, since the mechanics of the rupture (crater) formation are essentially the same. Accordingly, the effect of overburden thickness on these effects is described here from a classical cratering context.

For a given explosive loading density, crater size will at first increase steadily as the depth of burst (DOB) is increased. At some depth called the "optimum" DOB, the crater size will reach a maximum. For further increases in DOB, the weight of the overburden tends to suppress the formation

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of the crater. As the energy of the explosion becomes less able to throw ejecta beyond the edge of the crater, more material falls back within the crater boundary, thus reducing the apparent crater depth. The crater radius will decrease slightly until a DOB called the containment depth is reached, at which the crater completely disappears and is replaced by a mound of bulked soil or rock. Finally, the camouflet depth is that DOB at which little or no surface disturbance occurs, and the explosion forms only a subsurface cavity. Figures 1 (for soil) and 2 (for rock) from Reference 1 illustrate characteristic variations in crater parameters as a function of DOB.

The apparent crater radius decreases and approaches zero as the charge DOB approaches $2.0 \text{ m/kg}^{1/3}$ for soil or $1.2 \text{ m/kg}^{1/3}$ for soft rock (1.0 for hard rock). The limits are shown by the upper bound lines in Figures 1 and 2, respectively. Explosions at these DOB's are fully contained, producing only surface heaving. Therefore, munitions storage chambers with cover depths greater than 2.0 (soil), 1.2 (soft rock) or $1.0 \text{ m/kg}^{1/3}$ (hard rock) will not produce significant ejecta hazards from rupture of the overburden.

EXPLOSIVE COUPLING

If an earth-covered or underground storage chamber is completely filled with explosives, so that no empty volume remains, the explosive loading density will be approximately 1600 kg/m^3 . In most cases, however, the chamber is not completely filled, so the loading density is some fraction of this value. Explosive "coupling" refers to the intimacy of contact between a volume of explosive and the surrounding soil or rock. If a chamber is completely packed with explosives, the detonation is "fully coupled", with a coupling factor (f_{cf}) of 100%. As the explosive loading density is decreased, the coupling factor decreases proportionally.

Ground shock, cratering, and ejecta/debris throwout all decrease for lower coupling factors. The coupling factor can be estimated from Figure 3 (based on underground coupling experiments in halite and model ammunition storage chamber experiments at the U.S. Army Engineer Waterways Experiment Station). The effective charge weight (Q_e) is the product of the explosive weight (Q) and the coupling factor (f_{cf}) that applies for a given chamber loading density ($Q_e = f_{cf} Q$). The effective explosive weight can then be used

in Figure 1 or 2 to obtain predicted crater dimensions for a large detonation in an underground storage chamber.

EJECTA HAZARD CRITERIA

The debris hazard criteria given in the U.S. DOD Explosives Safety Standards (Reference 1) and the NATO AC/258 manual (Reference 2) consider two sources of hazardous debris: rock thrown by the overburden rupture and material blown through the access tunnel portal. The Explosives Safety Standards require a Inhabited Building Distance for debris of 610 m along and 15 degrees either side of the extended access tunnel centerline. The NATO AC//258 Inhabited building Distance for debris is 600 m over the same 30 degree arc.

For debris originating from rupture of the magazine cover, the Explosives Safety Standards give a hazard range of

$$D_{id} = f_d f_c Q^{0.41} \quad (1)$$

where D_{id} is the hazard range, m

f_c is a function related to the scaled overburden depth, m

Q is the explosive quantity stored in the chamber, kg

and f_d is a function of chamber loading density, given by the relation

$$f_d = 0.364 (Q / V)^{0.18} \quad (2)$$

where V is the chamber volume, m^3

The function f_c is given graphically in Figure 4 for hard rock (granite or limestone) and for soft rock (sandstone). The relation between the function f_d and the coupling factor (f_{cf}) is shown graphically in Figure 5.

The minimum overburden thickness above the chamber for the Shallow Underground Tunnel/Chamber Explosion Test was 9.4 m, giving a scaled (TNT-equivalent) overburden depth of $0.35 \text{ m/kg}^{1/3}$. The earth cover function, f_c , for this scaled overburden depth is $5.09 \text{ m/kg}^{0.41}$, from the "soft rock" curve of Figure 4. The loading density function calculates to be 0.77. Substituting these values in Equation 1, the Inhabited Building Distance for protection from debris from the Shallow Underground Tunnel/Chamber Explosion

Test is 236 m.

The NATO AC/258 debris criteria for a scaled cover depth of $0.35 \text{ m/kg}^{1/3}$ are given as

$$D4 = 5.10 Q^{0.41}, \quad \text{for hard rock} \quad (3)$$

and $D5 = 5.00 Q^{0.41}, \quad \text{for soft rock} \quad (4)$

These criteria were developed for a loading density of 270 kg/m^3 . A reduction is allowed for smaller loading densities. For the TNT-equivalent loading density of 66.4 kg/m^3 that was used for the Shallow Underground Tunnel Chamber Test, the correction factor for the NATO AC/258 "soft rock" criterion is 0.80. For hard rock, the Inhabited Building Distance for debris is 308 m before correction for loading density, and 246 m with the correction.

The current Explosives Safety Standards criterion for a debris hazard is a fragment or debris density of one hazardous particle per 56 m^2 . An analysis of the debris on the motion picture records of the Tunnel/Chamber test indicated that almost all debris seen on the film was potentially lethal (kinetic energy greater than 79 J), and thus considered hazardous. As shown in Figure 6, a debris density of one missile impact per 56 m^2 occurred at a distance of 656 m. This distance is 1.08 times the hazard range calculated by the Standards, and is 1.09 times the NATO AC/258 Inhabited Building Distance for debris range along the access tunnel axis.

The debris and ejecta collection on the Tunnel/Chamber Test was concentrated within a sector extending 45 degrees each side of the extended tunnel axis; therefore the effect of azimuth on debris range can only be based on data within this sector. These data are shown in Figure 7, where curves are drawn to approximate the debris limits at azimuths of 0, 20, and 40 degrees. As shown here, the distance to a debris density of one strike per 56 m^2 is 656 m, 447 m, and 287 m along the 0, 20, and 40-degree azimuths, respectively. For the Tunnel/Chamber Test configuration, Figure 8 compares debris hazard ranges, as a function of azimuth, based on criteria given in the Explosives Safety Standards and NATO AC/258, with ranges derived from actual debris data collected on the Tunnel/Chamber Test. As shown in the comparison,

both sources slightly underpredict the hazard ranges in front of this tunnel/chamber geometry and loading density.

EJECTA VELOCITY

The pre-and posttest locations of the artificial missiles used for the Tunnel/Chamber Test are given in Reference 4. The ejecta ranges are plotted versus their pretest locations in Figure 9. In this figure, "slant distance" is the distance from the center of the 20,000 kg charge to a missile's pretest or posttest position, as calculated from surface coordinates and elevation data. The symbols in Figure 9 identify missile pretest locations with respect to the surface ground zero (SGZ), which is a point on the overburden directly above the center of the explosive charge. FRONT denotes pretest missile locations down-slope from the SGZ. As shown in Figure 9, the test data indicates that missiles originating at locations down-slope from the SGZ (FRONT) travel the greatest distance, and those originating at up-slope locations (BACK) travel the least. All missiles were found down-slope from their original positions. The differences in displacement of missiles on the east side compared to those on the west side of the magazine is attributed to slope effects. The overburden surface dropped gradually to the east and rapidly to the west.

Launch velocities were computed for three artificial missiles using the known missile displacement and assuming a launch angle of 45 degrees. The calculated launch velocities are plotted in Figure 10, where a comparison is shown with results of previous tests Reference 5), which include data from storage wall debris tests, aircraft shelter detonations, and large-scale buried detonations, both tamped and untamped. The artificial missile launch data from the Tunnel/Chamber Test are in good agreement with the other data shown in Figure 10.

COMPUTED HAZARD RANGE

Ejecta range was computed from the launch velocity curves of Figure 10 using a trajectory algorithm obtained from Reference 6. A concrete missile mass of 454 kg, a storage chamber volume of 331 m³, and an explosive weight of 22,000 kg were assumed for these calculations (the storage volume and weight

correspond to the Tunnel/Chamber Test). The computed ejecta hazard ranges are plotted versus scaled cover depth in Figure 11. The cover depth (D) is scaled by two factors: the cube root of the charge weight ($Q^{1/3}$), and the chamber loading density to the 0.18 power ($q^{0.18}$). As shown in Figure 11, the computed ejecta hazard range for loading densities between 10 and 100 kg/m³ collapse onto a single curve when plotted versus scaled cover depth. Lighter loading densities give shorter calculated ejecta hazard ranges at shallow scaled cover depths, and approach the common upper bound curve as scaled cover depth increases.

A simple calculation was performed to estimate an upper bound of the overburden ejecta hazard range for the Tunnel/Chamber Test conditions (a loading density of 66.4 kg/m³). The WES computer code BREACHWL, which calculates the velocity of the breached section of a wall from an internal pressure-time history was used to compute ejecta velocity. The pressure-time history used was that recorded at the chamber wall (Gage C-3) on the Tunnel/Chamber Test, shown in Figure 12. Since the waveform ended prematurely due to cable failure at 40 msec the time history was arbitrarily extended to 320 msec by halving the pressure every 20 msec. The resulting velocity waveform is presented in Figure 13. A rock density of 2540 kg/m³ was assumed for these calculations. An estimated ejecta hazard range was obtained using the calculated peak missile velocity as input to the trajectory algorithm. These computations were performed for cover depths ranging from 4.2 to 56 m.

Measured and calculated ejecta hazard ranges are compared with the Explosives Safety Standard debris Inhabited Building Distance for hard and soft rock in Figure 14. The comparison includes data from the Shallow Underground Tunnel/Chamber Test (ejecta/debris collection and artificial missile recovery), the 100 kg/m³ launch velocity curve (Figure 11) and the BREACHWL calculated data. As seen in Figure 14, the experimental data is in good agreement with the ranges derived from the 100-kg/m³ launch velocity curve. The launch velocity curve crosses both Explosive Safety Standard debris Inhabited Building Distance curves at a cover depth of approximately $0.28 Q^{1/3}$ meters for a loading density of 100 kg/m³, which suggests that the Standard may not be conservative for shallower cover depths. Since the 100 kg/m³ launch velocity curve is in agreement with the measured Tunnel/Chamber

Test missile data and an upper bound to the ejecta hazard range data the Figure 14 also indicates that the Explosive Safety Standard is very conservative at cover depths much greater than $0.28 Q^{1/3}$ meters.

A similar comparison with the NATO AC/258 Inhabited Building Distance for hard and soft rock are shown in Figure 15. The NATO curves both intersect the 100 kg/m^3 launch velocity curve at a cover depth of $0.32 Q^{1/3}$ meters. This suggests that the NATO Inhabited Building criteria for debris may be unconservative at shallower cover depths, and overly conservative when the overburden thickness is greater than $0.32 Q^{1/3}$ meters.

CONCLUSIONS

The minimum cover depth given in the current NATO manual ($1.4 \text{ m/kg}^{1/3}$) for an underground magazine that is required to ensure containment of debris hazards is safety conservative and no change is recommended. The debris data from the Shallow Underground Tunnel/Chamber Test indicate that the Inhabited Building Distance for ejecta along the extended access tunnel centerline is unconservative and both the distance and the arc of coverage should be increased. Although the data are limited, the comparison of measured data and hazard ranges calculated from estimated launch velocities indicates that the Explosive Safety Standard and NATO AC/258 both are non-conservative for shallow cover depths, and overly conservative at greater cover depths. More data is needed to better define these relations.

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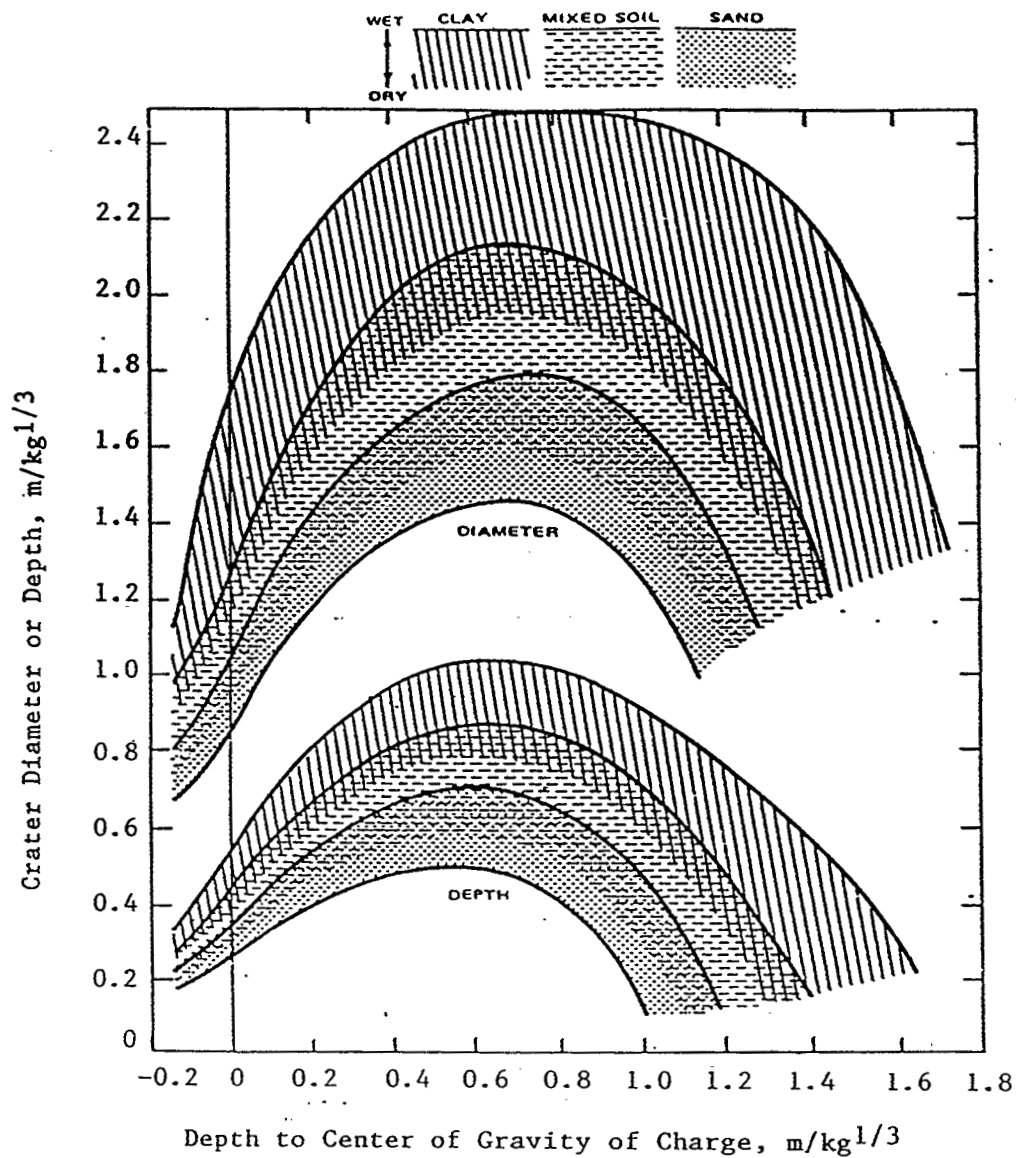


Figure 1. Apparent crater dimensions from explosions in various soils as a function of depth of burst (DOB) and general soil type.

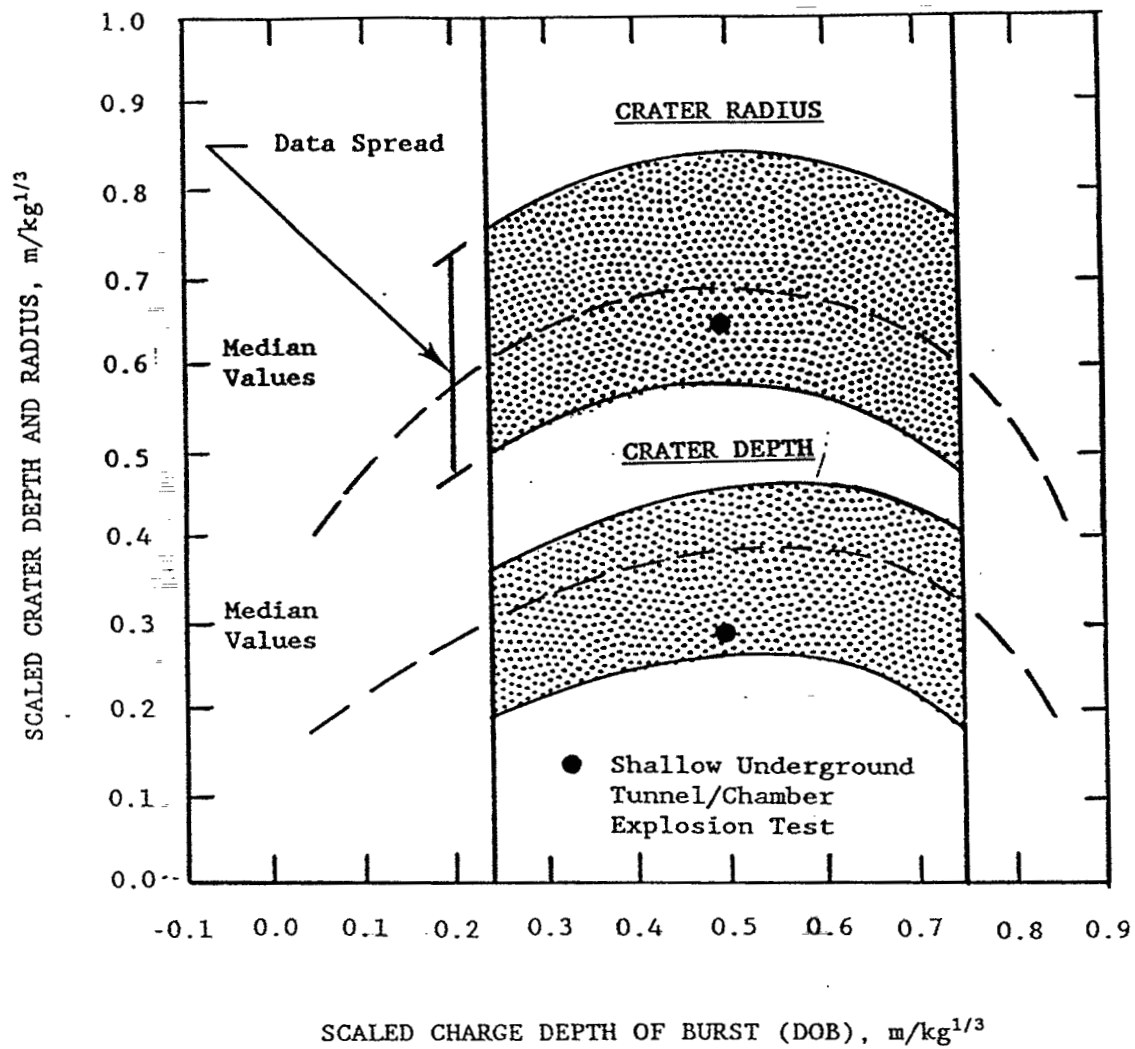


Figure 2. Apparent crater dimensions from explosions in rock as a function of depth of burst (DOB).

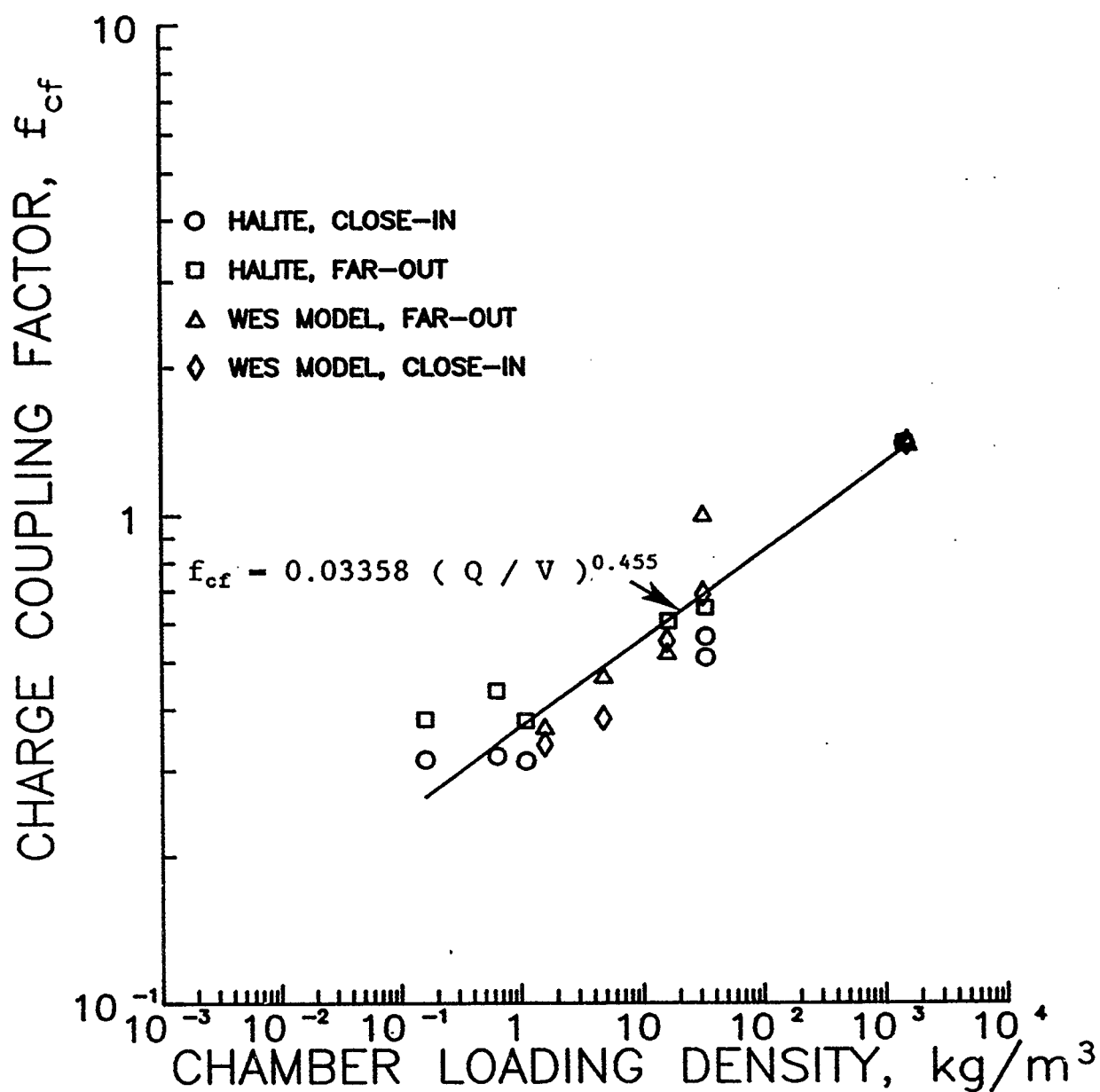


Figure 3. Charge coupling factor as a function of chamber loading density. Coupling data are derived from coupled and decoupled peak particle velocity measurements in halite and peak strain measurements from WES model tests.

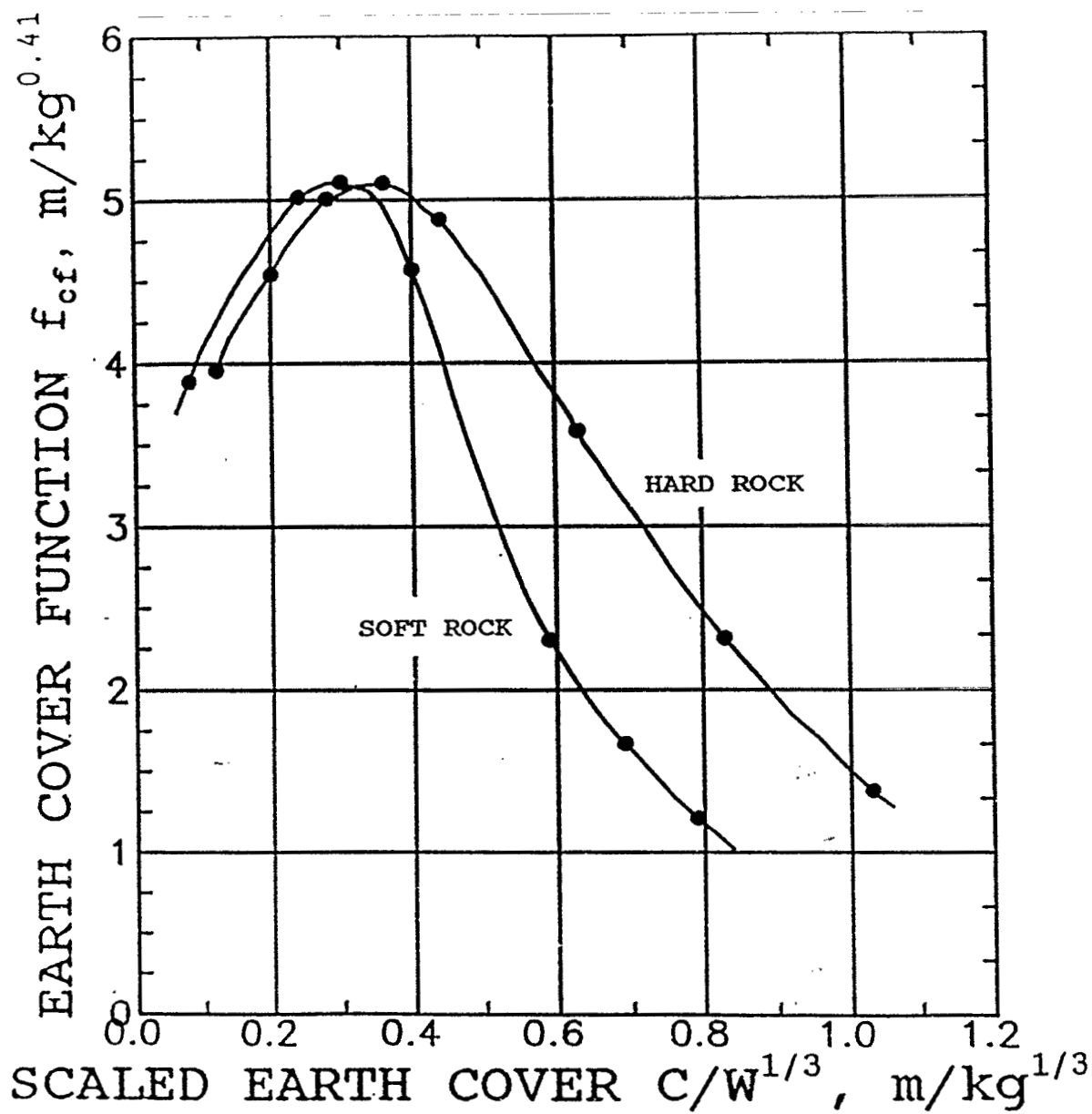


Figure 4. Earth cover function, f_c , for ejecta/debris versus scaled chamber earth cover depth; Ammunition and Explosives Safety Standards (Reference 2).

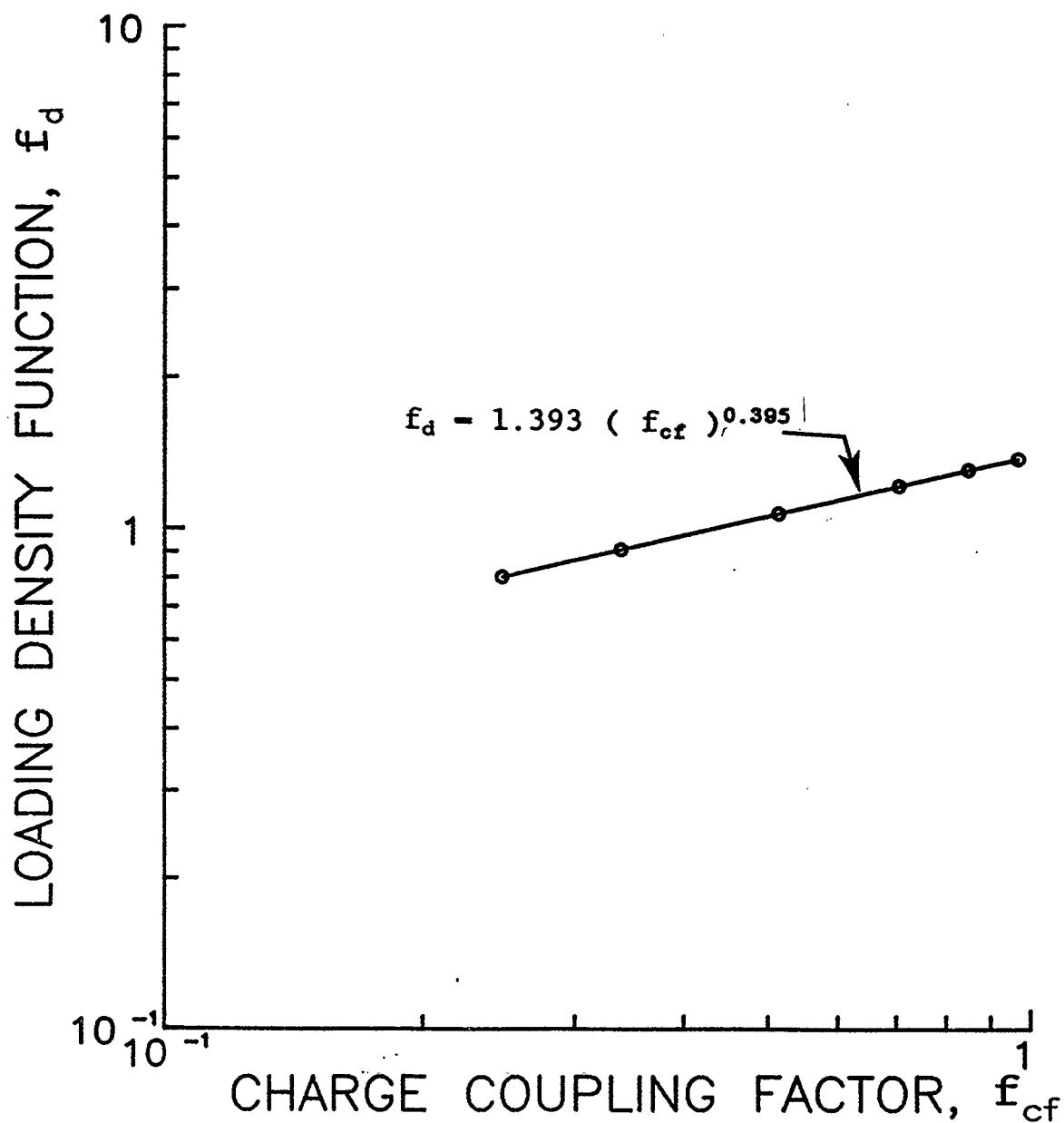


Figure 5. Charge loading function, f_d , for ejecta/debris versus charge coupling factor, f_{cf} .

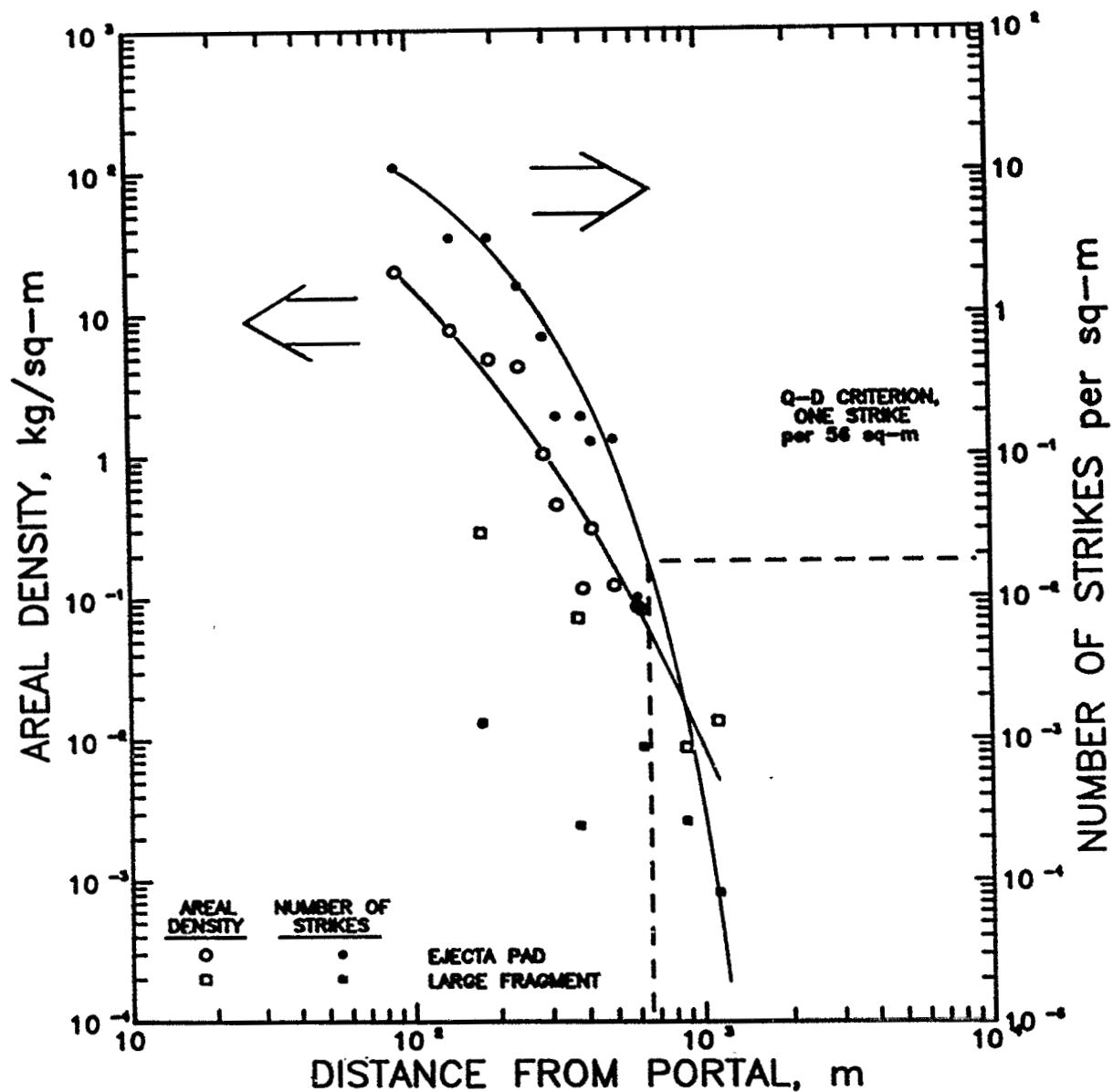


Figure 6. Areal density and number of strikes of natural missiles versus distance from tunnel portal, Shallow Underground Tunnel/Chamber Explosion Test.

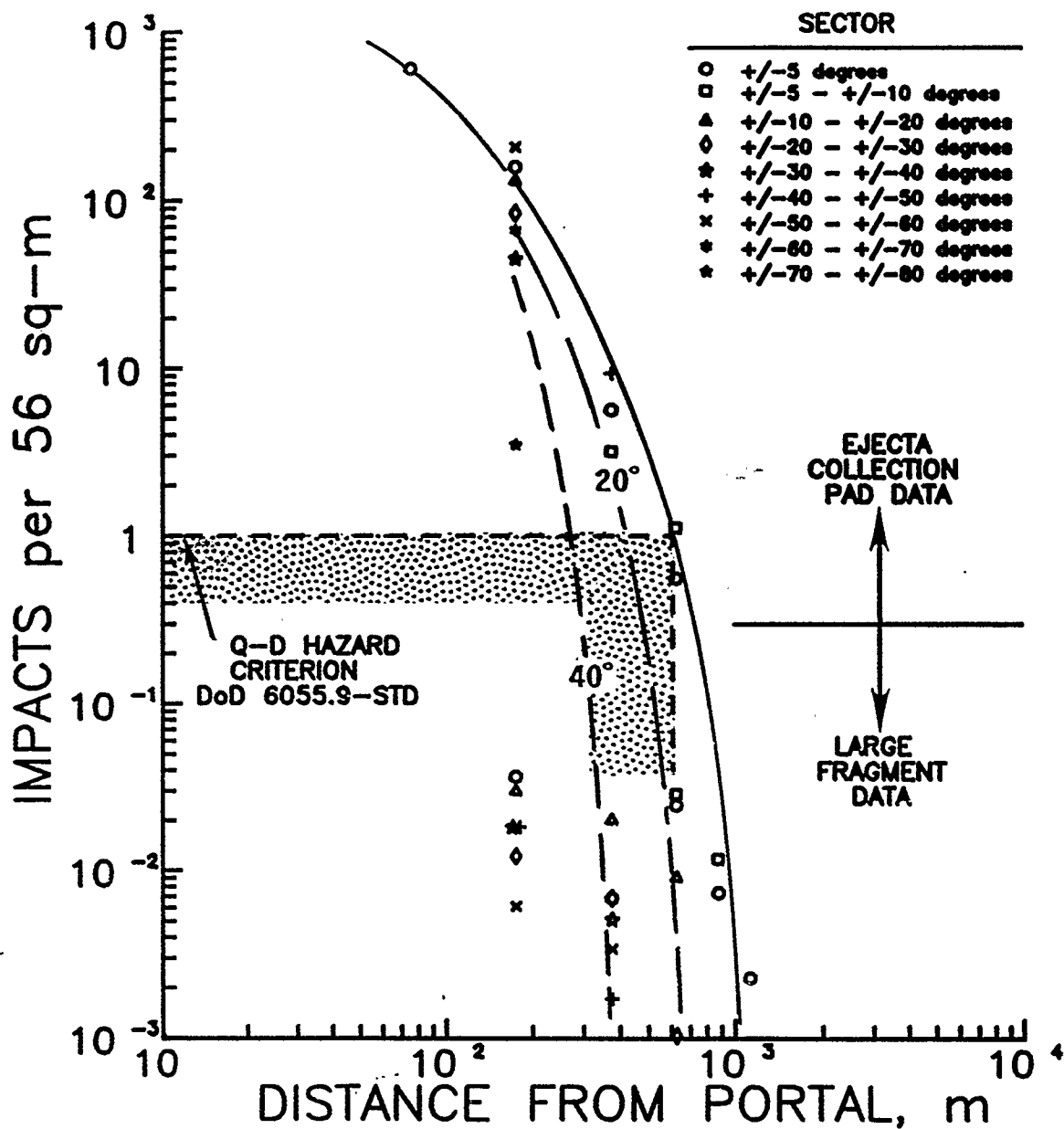


Figure 7. Ejecta/debris missile impact density versus distance from portal, Shallow Underground Tunnel/Chamber Explosion Test. Curves show general limits of missile density ranges along extended tunnel axis (0-degree azimuth) and with ± 20 degree and ± 40 degree sectors.

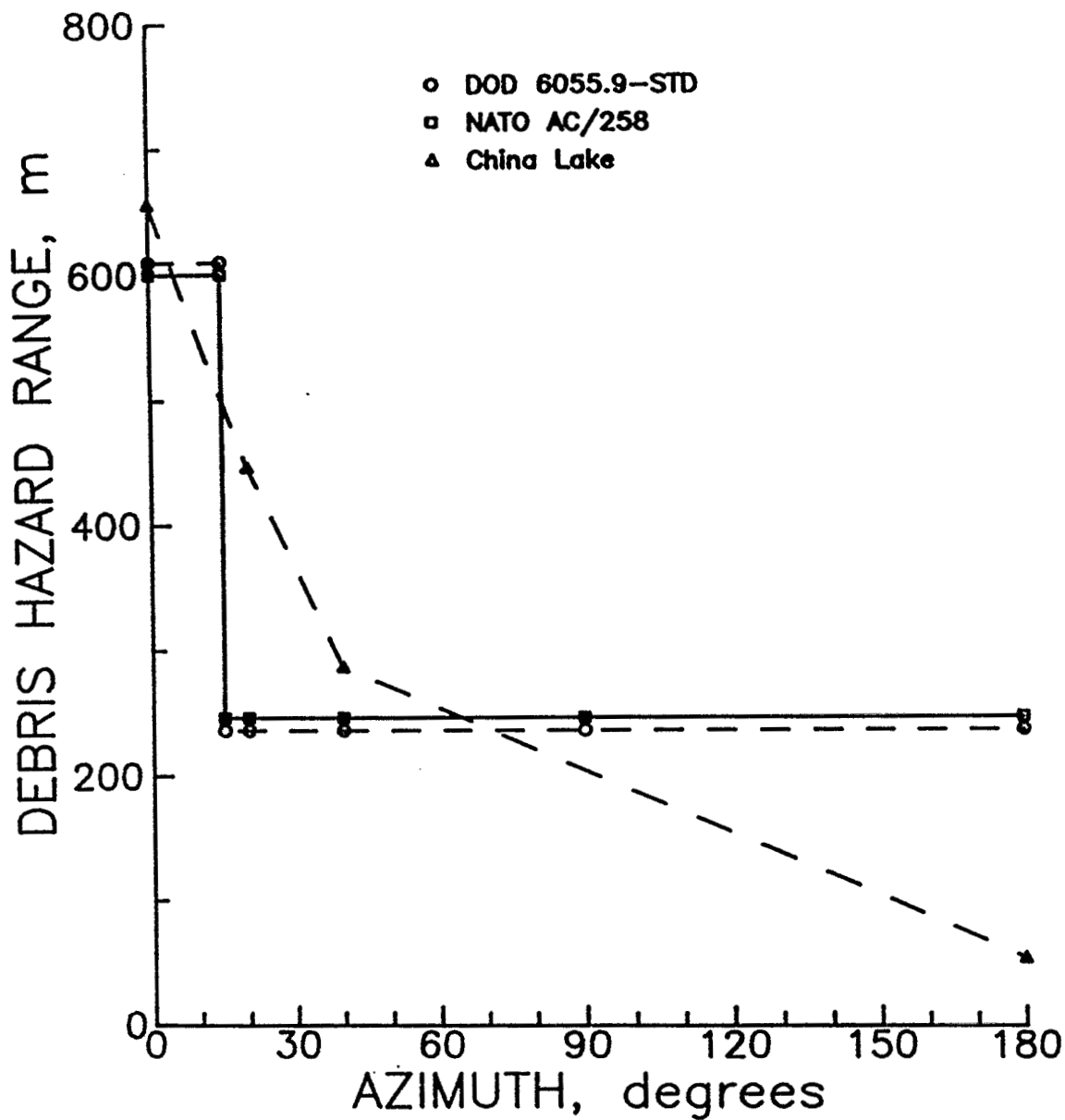


Figure 8. Inhabited Building Distances from debris hazards specified in the Explosives Safety Standards and NATO AC/258 for a 20,000-kg detonation, compared to ranges indicated by data collection on the Shallow Underground Tunnel/Chamber Explosion Test.

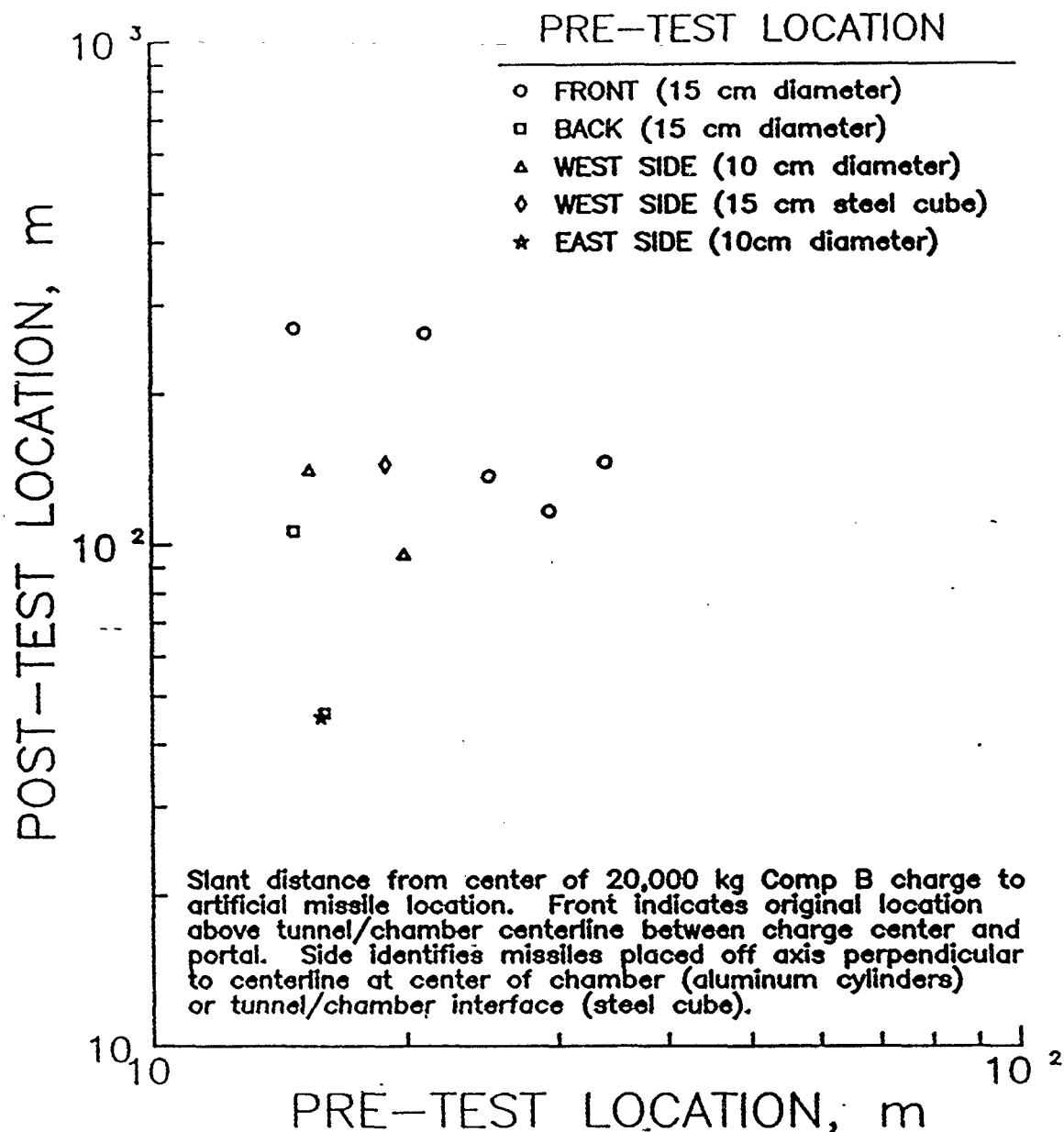


Figure 9. Artificial missile post-test versus pretest slant distance, Shallow Underground Tunnel/Chamber Explosion Test. Missiles were 10 and 15 cm diameter aluminum cylinders, 10 and 15 cm long, respectively. One 15 cm steel cube was also recovered.

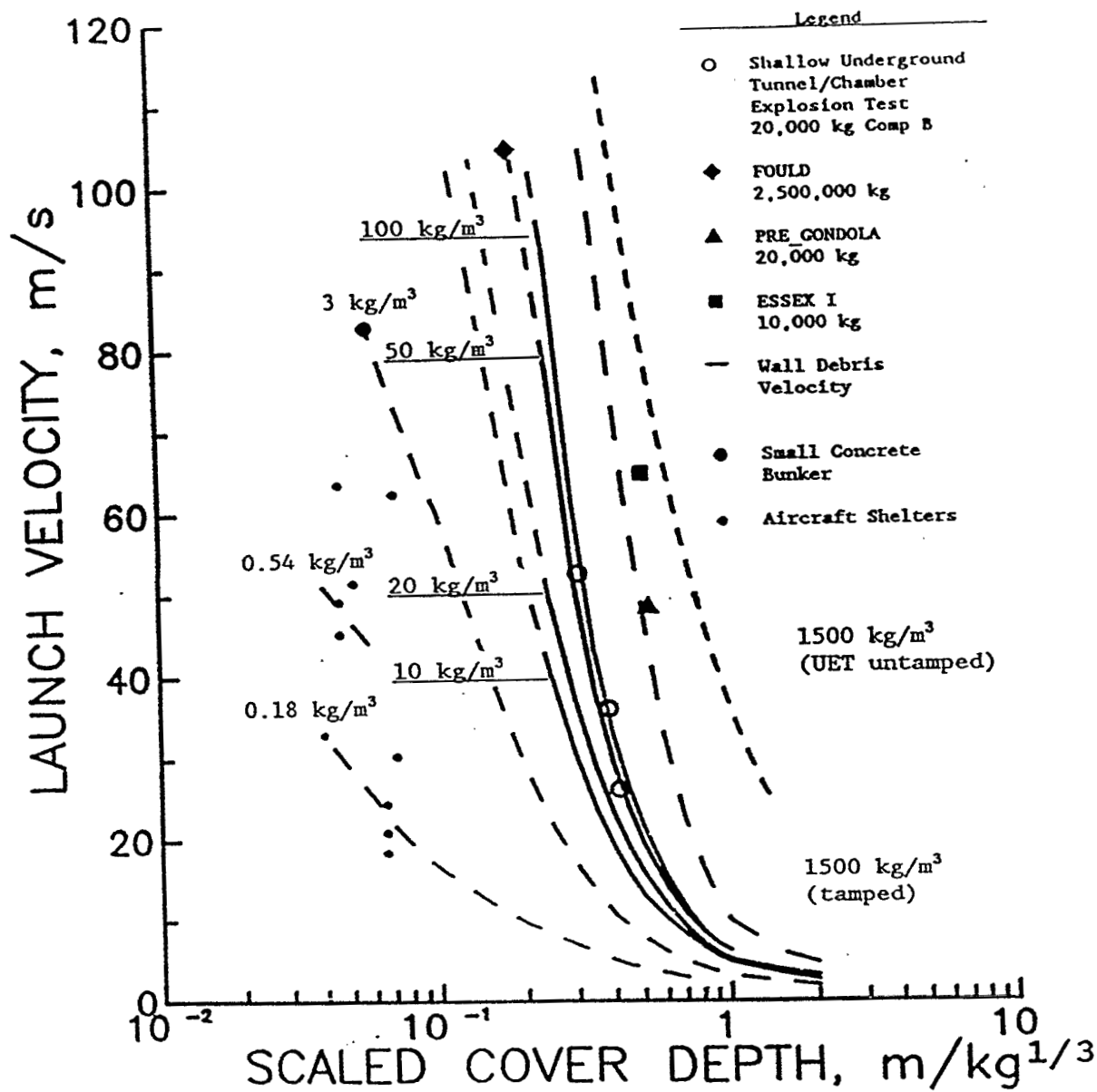


Figure 10. Launch velocity of cover rock ejecta from Shallow Underground Tunnel/Chamber Test, compared to ejecta velocities from other sources on previous explosive tests, (from Helseth, 1982). Scaled cover depth for Tunnel/Chamber Test varied from front of chamber to rear.

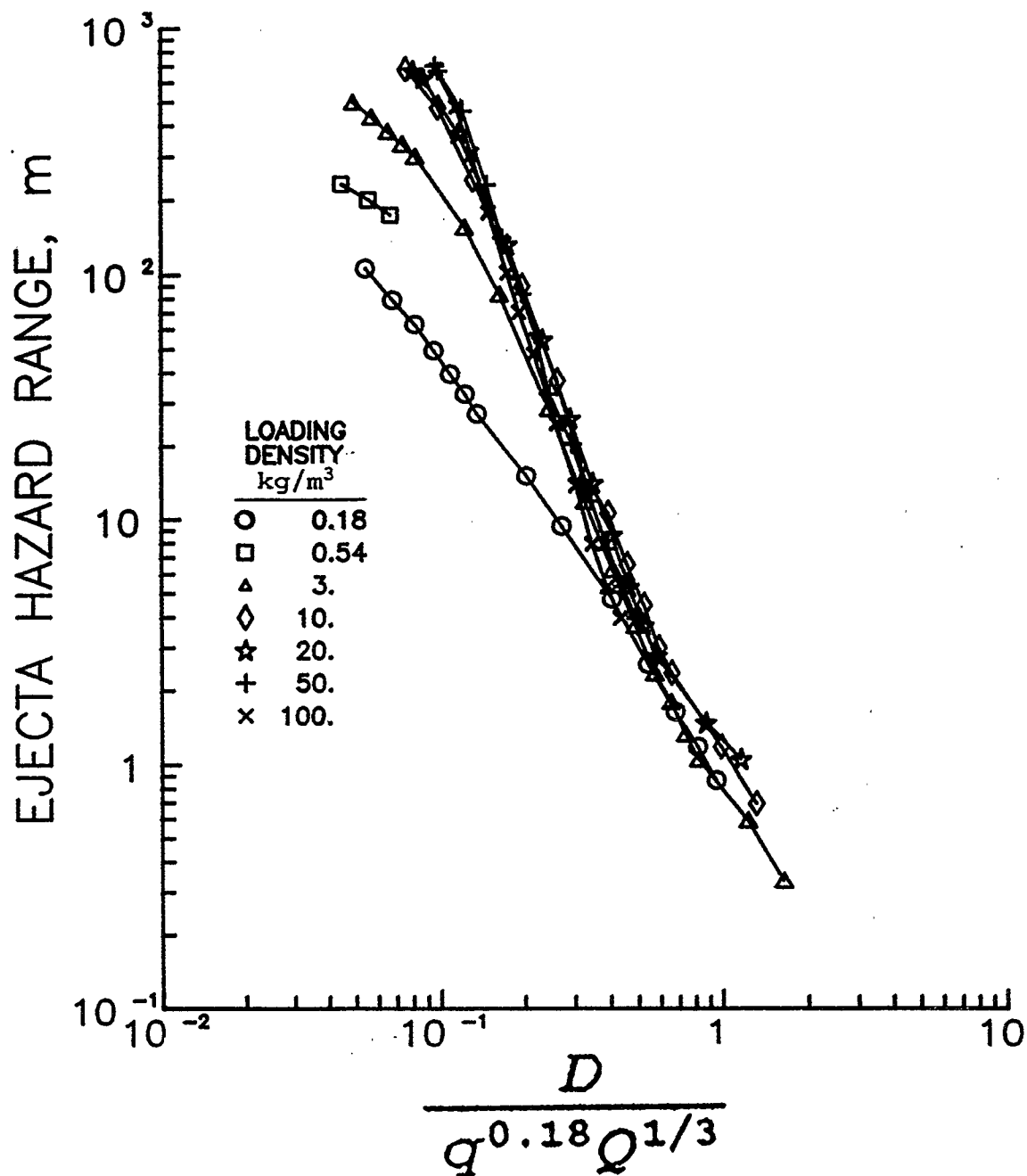


Figure 11. Ejecta hazard range, computed from launch velocity curves using trajectory algorithm with air drag, versus scaled cover depth. Cover depth (D) was scaled by product of loading density ($q^{0.18}$) times charge weight ($Q^{1/3}$). Chamber loading densities range from 0.18 to 100 kg/m³.

SIMPLIFIED WALL BREACH CALCULATIONS
INPUT CHAMBER PRESSURE

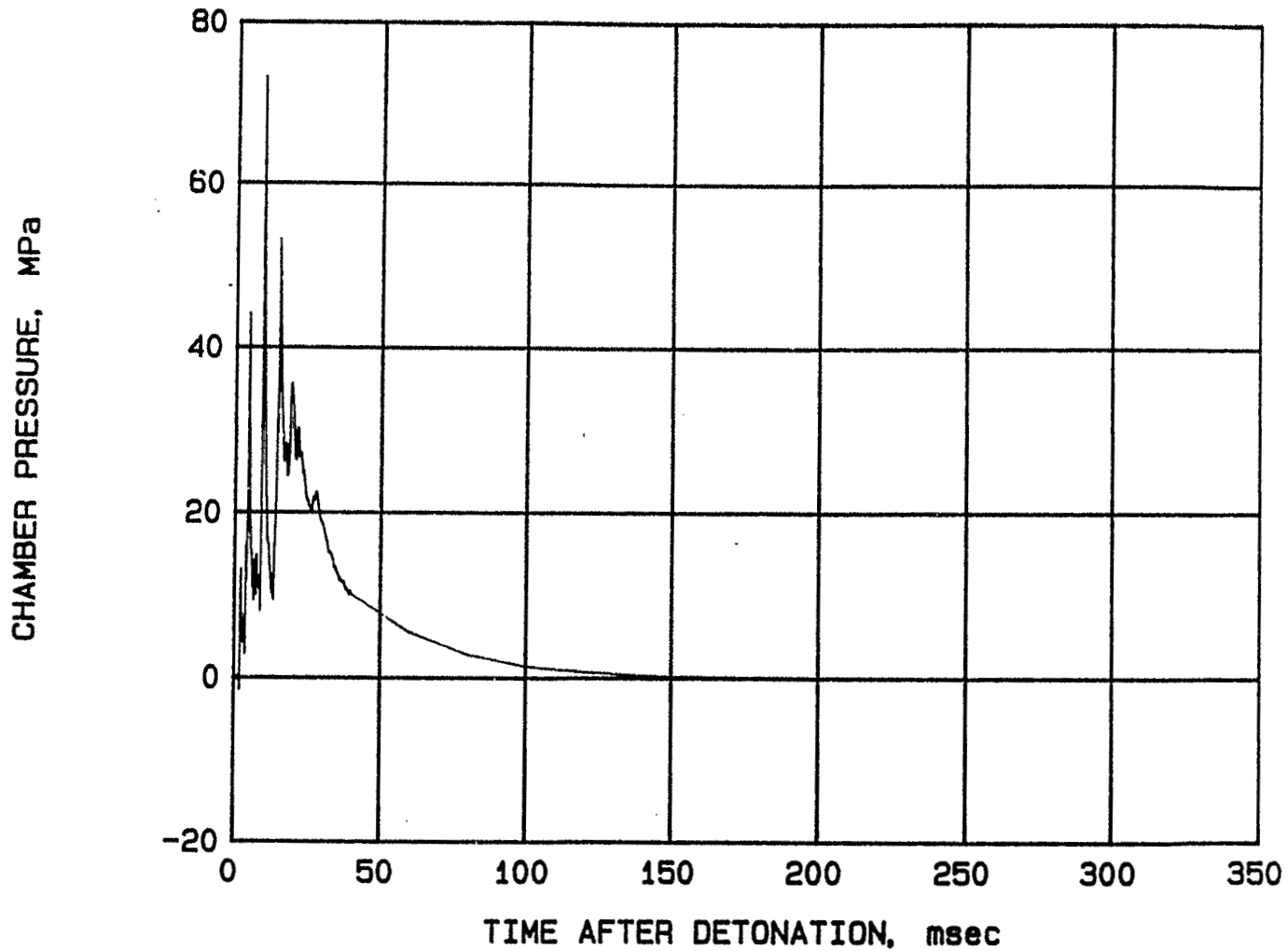


Figure 12. Shallow Underground Tunnel/Chamber Explosion Test chamber pressure-time history, Gage C-3. Instrumentation cable failed at 40 msec after detonation. Time history pressure decay has been approximated at later times by halving at 20 msec intervals.

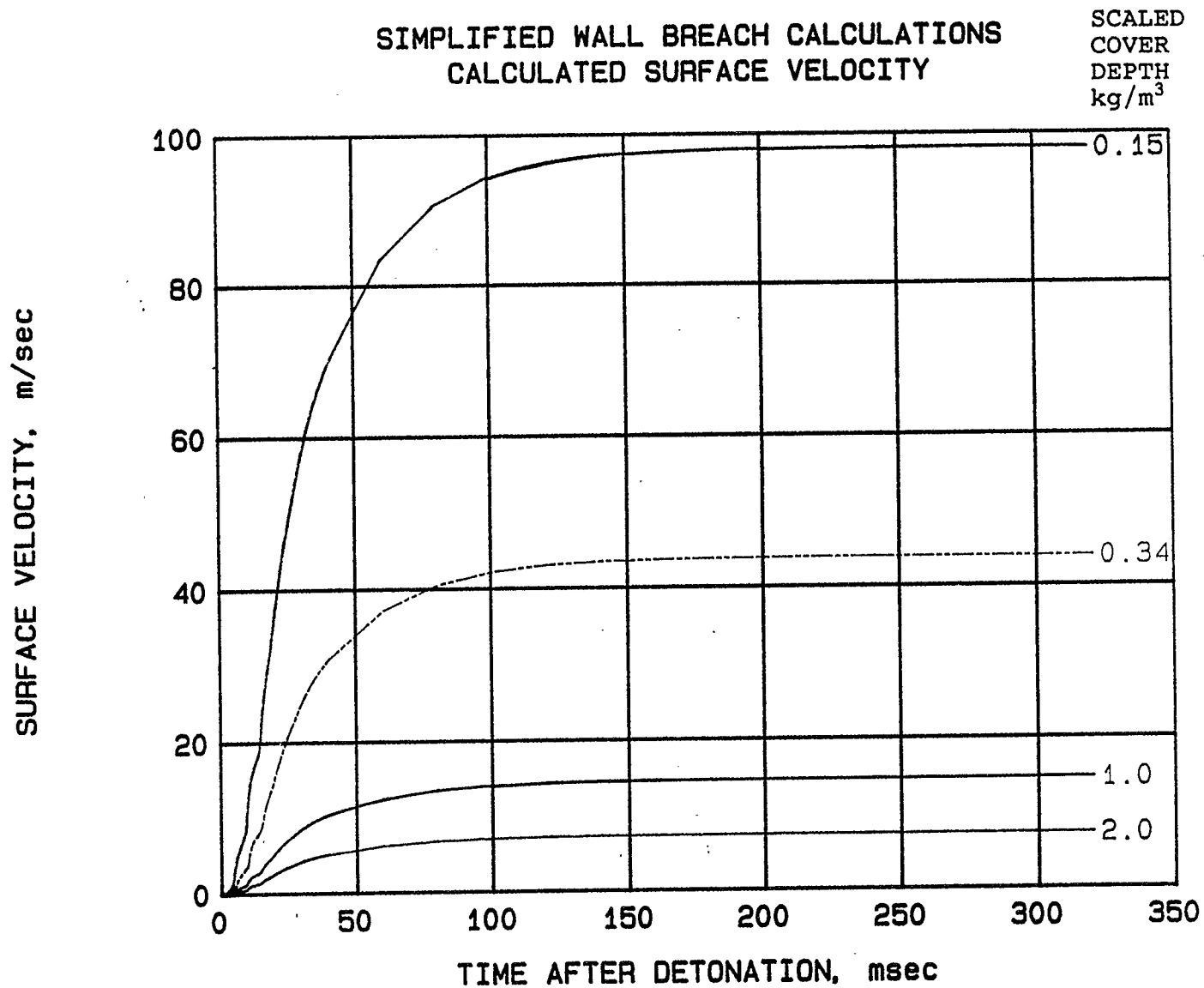


Figure 13. Surface velocity calculated with WES BREACHWL code versus time after detonation. The calculations used the measured pressure-time history given in Figure 12 for the chamber pressure function and a rock density of 2540 kg/m^3 was assumed.

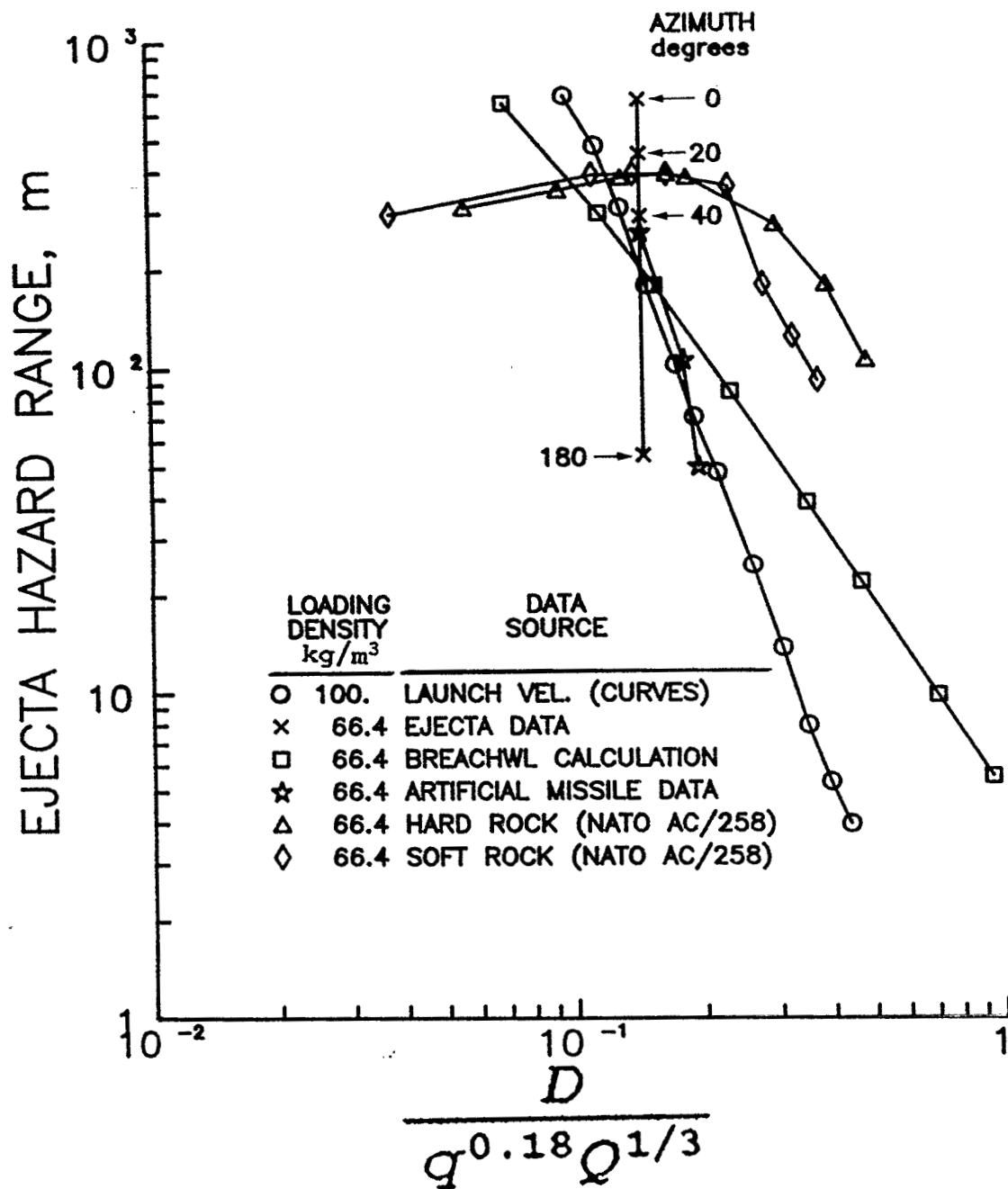


Figure 14. Ejecta hazard range versus scaled cover depth. Comparison of Inhabited Building Distance for debris from Explosives Safety Standards, measured data from Tunnel/Chamber Test, and computed distances (launch velocity curves and WES BREACHWL code).

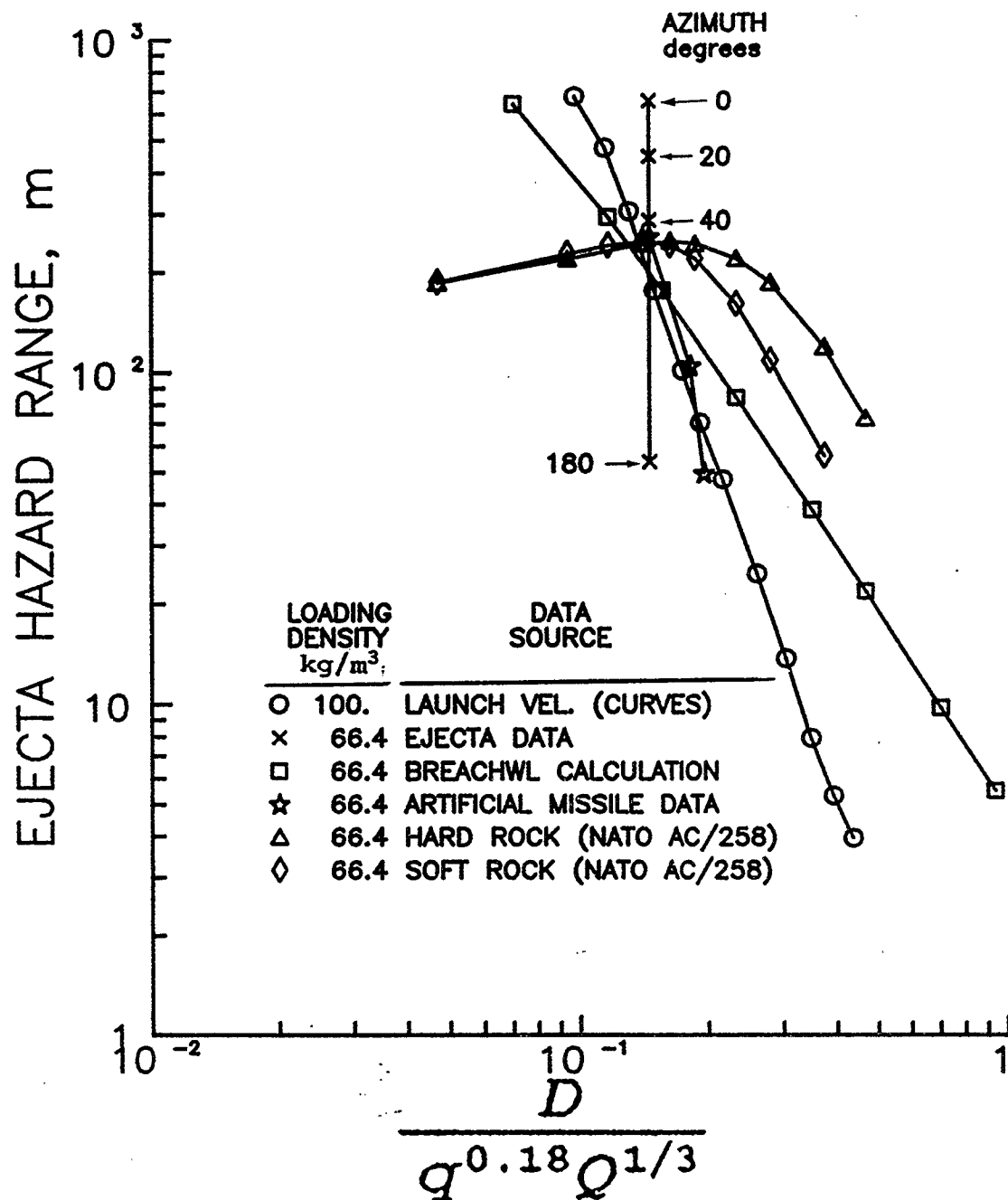


Figure 15. Ejecta hazard range versus scaled cover depth. Comparison of Inhabited Building Distance for debris from NATO AC/258, measured data from Tunnel/Chamber Test, and computed distances (launch velocity curves and WES BREACHWL code).